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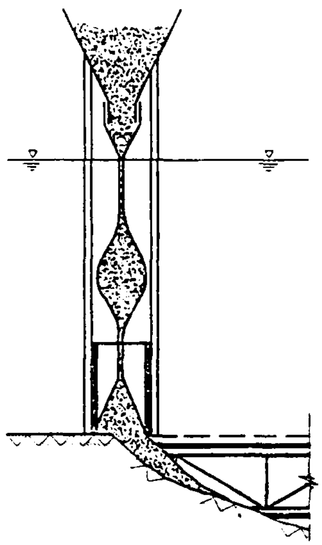
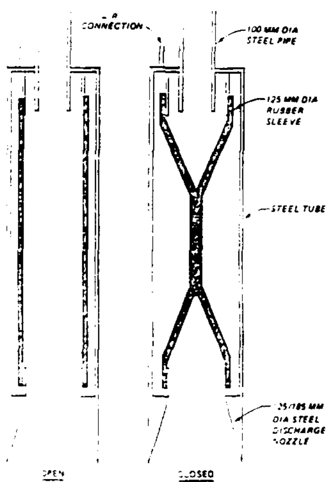
TECHNICAL REPORT REMR-CS-19

REVIEW OF THE STATE OF THE ART FOR UNDERWATER REPAIR USING ABRASION-RESISTANT CONCRETE





by

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COVER PHOTOS:

TOP — Hydro-Valve method

BOTTOM — A-Betong-Sabema pneumatic valve

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Concrete hydraulic structures that are subjected to severe abrasion require periodic inspection, evaluation, and repair. Not only are these procedures costly and sometimes disruptive, but repeated repairs also make guaranteeing the integrity of the underlying layers difficult. This review was conducted, on an international level, to identify new techniques and potential areas of research that might lead to more abrasion-resistant materials and more effective repair methods and that would avoid the high cost and disruptions associated with dewatering.

Topics of study in this review include: (a) underwater inspection, (b) concrete mixtures, (c) underwater placement of concrete, (d) underwater compaction of concrete, (e) polymer concretes and coatings, (f) surface preparation, and (h) support vehicles.

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PREFACE

The study reported herein was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32305, "Techniques for Underwater Concrete Repairs," for which Mr. Kenneth L. Saucier is Principal Investigator. This work unit is part of the Concrete and Steel Structures problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program sponsored by HQUSACE. Mr. James E. McDonald is the Problem Area Leader for Concrete and Steel Structures. The Overview Committee at HQUSACE for the REMR Research Program consists of Mr. James E. Crews and Dr. Tony C. Liu. Mr. Jesse A. Pfeiffer, Jr., was the Coordinator for the Directorate of Research and Development. Technical Monitor for this study was Dr. Liu.

The study was performed by Ben C. Gerwick, Inc., under contract to the US Army Engineer Waterways Experiment Station (WES). The study was conducted under the general supervision of Mr. Bryant Mather, Chief, Structures Laboratory (SL), and Mr. John M. Scanlon, Chief, Concrete Technology Division (CTD), and under the direct supervision of Mr. Kenneth L. Saucier, Chief, Concrete and Evaluation Group, the Contracting Officer's Representative. Program Manager for REMR is Mr. William F. McCleese, CTD. This report was edited by Mrs. Nancy Curtis.

COL Dwayne G. Lee, CE, was Commander and Director of WES during the publication of this report. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic metres
horsepower (electric)	0.746	kilowatts
kips (force)	4.448222	kilonewtons
inches	25.4	millimetres
miles (US statute)	1.609347	kilometres
ounces (avoirdupois)	0.02834952	kilograms
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per foot	1.488164	kilograms per metre
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	432.49842	kilograms per cubic metre
square feet	0.09290304	square metres
tons (2,000 pounds, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

REVIEW OF THE STATE OF THE ART FOR UNDERWATER REPAIR USING ABRASION-RESISTANT CONCRETE

PART I: INTRODUCTION

1. This report reviews the state of the art in international techniques for the Underwater Repair of Concrete Structures, with special emphasis on structures subjected to abrasion. The review was conducted to help identify new techniques and potential areas of research that might lead to more effective repair methods and that would avoid the high costs and disruptions associated with dewatering. Technical areas covered in the study include: (a) concrete mixture proportion, (b) concrete placement methods and equipment, (c) compaction of concrete in place, (d) underwater survey and inspection, (e) surface cleaning, (f) surface preparation including cutting and grinding, (g) polymer concretes and coatings, and (h) support vehicles.

2. The techniques reviewed are considered appropriate for the repair of hydraulic structures subjected to severe abrasion, especially stilling basins of dams. The depth of eroded concrete can range from a few inches to over 10-ft* cavities. Frequently, repairs have to be made in up to 70 ft of moving water while the structure is still in operation.

3. Recommendations resulting from the study can be divided into two areas: repair methods using current state-of-the-art technology and repair methods that may require further development but may yield superior results.

4. No one technique will be the most efficient and cost effective for all underwater repair jobs. Some techniques that use sophisticated and capital intensive equipment are suited for centralized coordination, while many techniques are direct enough to be used effectively for local, independent operations.

5. Abrasion can impose stringent performance requirements upon the wearing surface of a stilling basin. Repeated repairs make guaranteeing the soundness of the underlying layers difficult; therefore, more sophisticated, higher performance repair methods that can provide a more wear-resistant

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

surface should be considered, even though these techniques may require more initial planning and expense.

6. In general, denser, stronger, and more ductile materials provide greater abrasion resistance. Indications are that cement-based repair materials may be easier to apply if suitable abrasion resistance can be obtained. High-strength concrete with abrasion-resistant aggregate has demonstrated good resistance to wearing, and an important part of the study is to examine the maximum strength limit for concrete that can really be placed underwater. High-ductility concretes such as polymer cement concrete also merit due consideration. The use of pozzolans such as condensed silica fume has markedly increased the abrasion resistance of concrete.

7. The state-of-the-art review indicates that numerous innovative underwater repair techniques exist internationally which the Corps of Engineers could utilize to significantly improve the effectiveness of repairs made to hydraulic structures subjected to abrasion damage. Areas meriting further investigation include: (a) underwater compaction, (b) fiber-reinforced concrete, (c) high-strength concrete, and (d) field tests correlating laboratory results with in situ performance.

PART II: UNDERWATER INSPECTION AND SURVEY

8. Good underwater surveys are essential to any repair operation. Surveys are used to determine the extent of damage; the presence of debris, sediments, and organic material; and the best method of repair. They are also used to monitor the work in progress and to evaluate the quality of the repair performed.

9. Traditional inspection methods--visual and sound--may be adequate for most jobs; however, new techniques using robotics and higher resolution sounding systems offer options and versatility not possible before. Regardless of the inspection system used, a reference system to clearly identify the location of the area under examination should be established.

Robotics and Remote Vehicles

10. Robotic systems can be connected to a fixed working structure, or they can be remotely controlled mobile craft tethered to the surface with control cables. A remote-controlled vehicle has been developed by the Dutch for underwater inspection work at the Eastern Scheldt Storm Surge Barrier. The Portunus is a 6.0 m long by 4.0 m wide by 2.0 m high, tracked, bottom-crawling vessel capable of conducting surveys with a resolution of 0.5 cm in turbid water with velocities to 2.5 m/sec and depths from 15 to 45 m. The craft employs six television cameras fitted with special perspex lenses, four high frequency transducers, and sonar.

11. A single umbilical connects the Portunus to the support vessel, Wijker Rib. This cable carries the electrical power supply and electronic data to the crawler, maneuvers the vehicle in any desired pattern, and returns data to the control room on the support vehicle. As the data are gathered, they are stored in memories and then sent to the control room in time gaps. In addition to being distributed over a number of visually checked monitors, the information is stored in the computer and on videotape.

12. When the Wijker Rib was converted to a support vessel for the Portunus, a special crane had to be designed for deployment and recovery of the crawler. Underwater, the Portunus weighs approximately 4.5 tons, half its real total weight. As soon as it is lifted out of the water, the crane has to

carry the full load of the 9 tons, which causes enormous pressures in the lifting mechanism. Also, the crane has to compensate for the swell when the crawler is launched or recovered.

13. For a period of 3 years, the Portunus will check the 198 mattresses on which the 66 monolithic piers will be placed. Each mattress is 40 by 200 m and weighs 5,500 tons. The crawler will determine whether each mattress is exactly positioned in undamaged condition and whether sand, which can cause serious inaccuracies, has been deposited on the mattresses.

14. Bottom-crawling remote vehicles are probably most appropriate for use in stilling basins, although numerous nonbottom contact, remotely operated vehicles have been developed for underwater inspection. The Trigla, a nonbottom contact vehicle developed by the Dutch, is worthy of note because of its size. It is tubular (900 mm long by 42.5 mm diameter), self-propelled, free-floating, and equipped with lights, cameras, and pressure sensors. It was used to inspect the gap between the foundations of the precast piers and the sand layer for the Eastern Scheldt Barrier project.

Acoustic Contouring

15. The integrity of concrete structures depends mainly on their resistance against corrosion. Even in good quality concrete, corrosion underwater may be caused by cracks.

16. Acoustic inspection techniques do not require divers, can be used in low-visibility conditions, and can make examinations through surface layers of sediment. Acoustic inspection can be used in two modes of operation appropriate for use in stilling basins: (a) sonar or echo sounding, from near the surface or by a towed underwater "fish," or (b) ultrasonics, a local high-resolution underwater acoustic system.

17. The sonar method is well suited to mapping large areas with resolutions to the size of small ruts. However, a local high-resolution acoustic inspection can identify features as small as cracks in concrete. Ultrasonics can be useful in determining the degree of deterioration of the abraded concrete when cracking, spalling, and pitting have occurred. Because of the aggregates in concrete that interrupt or interact with the sound waves, ultrasonic techniques that do not penetrate too deeply into the concrete should be

used. Two such techniques are acoustic microscopy and the "leaky Rayleigh wave" methods.

18. Acoustic microscopy is like a photograph that is not affected by murky water, soft marine growth, nor loose debris filling the crack. A highly focused beam of ultrasound is transmitted and received by a single transducer as it sweeps back and forth across the surface to be examined. The signal is reflected off the surface of the concrete, and a point-by-point acoustical picture of the concrete surface is generated. The location, orientation, and width of any cracks or pits are identified.

19. After the width and extent of the cracking or pitting have been identified, the "leaky Rayleigh wave" technique can be used to determine the depths of the cracks or pits. Rayleigh waves are comparable to the waves that can occur on the free surface of a body of water. These waves are created by an ultrasonic beam directed to the concrete surface at a specific angle. These waves radiate back into the water and are received by a separate transducer. If the waves encounter a hole in the concrete surface, they travel along the surface of the hole, thus providing a measure of the crack or pit. The use of narrow beam transducers avoids "noise" in this system.

Visual Inspection

20. Still cameras and remotely controlled video and movie cameras provide an important means of underwater visual inspection. Remotely operated cameras provide a permanent record that can be interpreted later and electronically enhanced. Also, they do not require the stringent safety practices necessary with the use of divers.

21. Sinitalia s.p.a., a division of Sinmast Italia s.p.a. of Lendinara, Italy, performed the diving work during the repair of Tarbella Dam in Pakistan. Sinitalia divers are skilled in numerous underwater procedures: metal carpentry, welding, burning, oxygen lancing joint repair, painting, bonding with epoxy paste, and demolitions.

PART III: SUPPORT VESSELS

22. The development of appropriate support vessels can greatly facilitate the performance of high quality repair work. While it is possible to perform some jobs from the shore, projects with a high degree of sophistication usually require some type of support vessel.

Floating Pontoons and Barges

23. Floating pontoons and barges, the simplest form of support vessel, provide a platform from which to work. Making these vessels stable during heave, pitch, and roll is important, especially during tremie or pumped concrete operations. Stability can be provided by multiple anchor lines, a good metacentric height, a wide area at the waterline, or strategic placement of extra buoyancy tanks.

Jackup Barges

24. Jackup barges for rivers and shallow waterways can provide a number of advantages for underwater repair work: (a) they can provide stability for surface preparation, repair, and inspection operations; (b) they can be used to guide and control such automated equipment as high-pressure water jets, surface grinding equipment, and monitoring equipment; (c) they are suited for handling and placing large prefabricated panels; and (d) they can serve as a counterweight for work such as compacting zero-slump concrete with a vibratory pressure plate.

Robotics

25. Remotely operated vehicles (ROV's) would make conducting underwater concreting operations from a support vehicle or from the side of a stilling basin possible. If the initial cost of developing ROV's for underwater use could be amortized over several projects, this equipment could prove to be valuable in repairing stilling basins.

PART IV: SURFACE PREPARATION

26. Proper surface preparation is essential for adequate bonding between the old and the new material. Virtually all surface-cleaning techniques that can be used on dry land can also be used underwater.

Sediment Removal

27. Sediment and debris should be removed from the entire stilling basin as a first step in repair operations. The type of sediment or debris to be removed determines the type of removal system to be used. If the rate of sedimentation or organic growth is high, the elapsed time between the surface preparation and the repair work could be critical for some applications. In such cases, back-flushing the concrete surface just prior to the repair work would put any residual sediment into suspension.

High- and Ultrahigh-Pressure Water Jets

28. High-pressure water jets can be used in surface preparation to jet away loose sediment and debris, break up and remove substandard concrete, cut rough grooves for better bonding, and prevent feathering around the perimeter of an excavated area by cutting a precise edge. Ultrahigh-pressure water jets can be used to trim the perimeter of an eroded area. Water jets can be used by divers or remotely controlled from the surface.

29. The effectiveness of waterblasting is demonstrated by automatic, high-pressure waterblasting machines that can remove deteriorated concrete from the surface of bridge decks. Working in a range of 17,000 psi, these machines are capable of cleaning 2,000 sq ft with removal depths of 3 to 6 in. in 24 hr using banks of jets up to 13 ft wide. The high-pressure jets cut grooves into the underlying concrete; these grooves greatly increase the bond between the old and the new material.

Doweling

30. Doweling should be considered when adequate bond cannot be guaranteed and methods such as water jetting are not considered suitable.

Typically, doweling has been done by a diver who drills into the underlying material and bonds a steel bar into the hole with a cement or an epoxy grout. Because this method is labor intensive, the number of dowels that can be effectively placed is limited. However, the use of percussively placed dowels allows a greater number of smaller dowels to be placed over a larger area. The Naval Civil Engineering Laboratory has developed power-actuated dowels for use underwater. Almost 600 prestressed rock anchors were used on Tarbella Dam in Pakistan to secure areas of the repaired floor of the stilling basin against uplift forces from the water.

31. CemBol T, a cartridge product made of wet-strength paper with a mixture of cement and special additives, provides a simple method to quickly and effectively anchor large doweling bolts underwater. CemBol T, which is marketed by Sweden, provides a totally embedded, corrosion-proof bolt. No rotation is required when the bolt is fastened--either horizontally or vertically--and no equipment has to be cleaned. After 3 hr at +10° C, the bolt can support a load of up to 5 tons/m; after 24 hr, the loading can be more than 15 tons/m.

PART V: CONCRETE MIXTURE PROPORTIONS AND PROPERTIES

32. Concrete referred to in this report is portland-cement concrete. This concrete is relatively inexpensive and easy to obtain and use; it complements or exceeds the mechanical properties of most concrete structures. Concrete technology offers a variety of options for controlling the properties of fresh and hardened concrete: (a) selection of the mixture components, (b) variations in the mixture proportions, (c) inclusion of concrete admixtures, (d) control of the temperature of fresh concrete, (e) incorporation of fiber reinforcement, (f) compaction and vibration while placing the concrete, and (g) processing the concrete after it is placed.

33. Two very important factors control the type of concrete to be used for underwater repair: the workability of the fresh concrete and the abrasion resistance of the hardened concrete. To some degree, these two factors work against each other: a dense, strong concrete that would be abrasion resistant requires a mixture with a very low water-cement ratio and the inclusion of such materials as microsilica flume; these same properties reduce the workability of the mixture. Inadequate workability that results in voids and soft spots also reduces the abrasion resistance of the concrete. The degree of workability of the concrete needed for a repair job depends upon the chosen method of placing and finishing the concrete.

Rheological Properties

34. The rheological properties of the concrete are very important as traditionally no compaction or treatments are applied to the concrete after it is placed underwater. Underwater placement by the tremie method or by pumping calls for a mixture with good mobility so it will spread away from the discharge nozzle; however, the concrete must not segregate. The addition of admixtures can reduce segregation, but if the cement content is high, the mixture can become sticky, resulting in a rough or uneven surface. Pumping the concrete can drive out free moisture; segregation can cause the aggregate to bridge the pumping line, causing blockages. The use of superplasticizers to increase the fluidity of the concrete can create rapid slump loss, especially if the temperature of the concrete rises because of excessive mixing or friction. Excessive bleeding can also lead to unacceptable results:

(a) reduced concrete strength because of worm-hole from migrating water and from bleed water accumulating beneath the aggregate; (b) the formation of a weaker mortar layer at the surface of the concrete; (c) poor bond between concrete and steel reinforcement bars or fibers; and (d) the potential formation of void beneath prefabricated panels.

35. No single test can measure all of the rheological properties of fresh concrete; therefore, several methods should be used. The slump test, the flow test, the two-point workability test and the tremie tube method are used most often. Manufacturers of concrete containing an antiwashout admixture recommend a 30-sec delay between the removal of the cone and the measurement of the slump test or the administering of the flow test to obtain an accurate measure of the flowability of the concrete. A test has been developed to estimate the cohesiveness of the concrete by measuring its mass before and after it falls through a column of water.

High-Strength Concrete

36. The abrasion resistance of concrete is influenced by different factors, one of which is strength (Smith 1951). High-strength concretes to 8,000 psi increase the abrasion resistance of concrete; above 8,000 psi, concrete with hard fine and soft, coarse aggregate may have greater abrasion resistance than concretes with both hard fine and coarse aggregate. These general findings are supported by work done by Terry Holland on the Kinzua Dam (Holland 1983), Tony C. Liu (Liu 1983), and Norwegian contractors on both light and normal weight concrete.

37. Liu contends that the rate of increase in abrasion resistance drops off gradually with increasing strength of the concrete. He further concludes that the way the aggregate breaks down under abrasion affects the abrasion resistance: limestone is more susceptible to crushing, which can accelerate abrasion; chert tends to chip and spall under abrasion. Nevertheless, the better strain compatibility between the strong, hardened cement paste and a softer to moderately stiff coarse aggregate may reduce the levels of stress around the coarse aggregate, thus increasing the toughness and abrasion resistance of the concrete. Work on very high-strength concrete over 12,000 psi, 28-day compressive strength indicates this type of concrete has excellent abrasion resistance. Currently, concrete mixtures of this strength are

difficult to place in dry or underwater areas. Precast panels or some form of vacuum or pressure processing would provide an alternate means of placement.

Vacuum and Pressure Processing

38. Although neither vacuum nor pressure processing is commonly used for underwater treatment of concrete, both processes could be readily adapted for use underwater. Both processes increase the strength of the concrete by compacting or removing voids; however, vacuum processing tends to be more efficient because it removes excess surface air and both surface and internal water from the concrete.

39. While pressure processing requires an external source of pressure such as a pressure plate, a roller compactor, or hydraulic pressure, vacuum processing can use the ambient pressure as a source of compaction. For vacuum processing to work properly, some portion of the fresh concrete must be exposed to the ambient pressure so the excess water can be squeezed toward the vacuum. A filter mat consists of a watertight backing with a gasket around the perimeter and layers of porous filter material in the space formed by the gasket. The filter material prevents the cement and fines from being drawn off with the excess water when a vacuum is applied. Mats up to 50 sq m have been used on land (Orchard 1979). Conceivably, a system such as that used to deploy mats for the Netherland's Eastern Scheldt Barrier project could be used to deploy vacuum mats for underwater vacuum processing.

40. Vacuum processing on land can reduce the water-cement ratio of concrete from 0.5 to about 0.35. T. C. Liu (Liu 1983) has shown that vacuum processing at 12 psi for 15 min can increase the abrasion resistance of concrete with an initial water-cement ratio of 0.54 by 39 percent. Underwater vacuum processing could be expected to produce better results. The surcharge of waterhead at a depth of 66 ft would contribute two atmospheres of pressure in addition to the atmospheric pressure; therefore, maintaining a suction pressure 3 or 4 times that available on land would be possible. Vibration should be used with vacuum or pressure processing to help close voids within the concrete.

Fiber-Reinforced Concrete

41. The use of fiber-reinforced concrete to repair hydraulically eroded concrete structures has met with mixed results. Adding steel fibers to concrete increases its toughness but not its abrasion resistance. Laboratory and field research indicates that when the concrete is subjected to hydraulic abrasion, the steel fibers can pull out, disrupting the matrix of the concrete and accelerating abrasion damage. This acceleration appears to be closely related to the bond between the steel fibers and the concrete. Densit Wear Resistant II (a product of Densit A/S) exhibits excellent abrasion resistance even though it contains a minimum quantity of only 1.5 steel fibers by volume. This resistance is related to the excellent bond Densit has with the steel fibers. Fiber-reinforced concrete is part of the experimental work done by Ben C. Gerwick. This work includes the use of "Harex" steel fibers from West Germany. "Harex" has good bonding properties and a decreased tendency to ball in the mixer.

Concrete Admixtures

42. Recent developments in concrete admixtures have made possible the placement of concrete underwater with higher abrasion resistance than was possible in the past. A number of proprietary products, using variations of the same basic technology, have been developed around the world.

Antiwashout admixtures

43. Antiwashout admixtures are used to:

- a. Minimize the washing out of fines and cement from the concrete when it is in contact with water.
- b. Prevent segregation of the concrete.
- c. Reduce bleeding of the mixture.
- d. Decrease the migration of moisture within the concrete mixture.
- e. Inhibit water entrainment as the concrete passes through water.

44. Generally, these admixtures contain cellulose derivatives that can increase the water retentivity and the mixture thixotropity by binding up the free water in the mixture, while allowing it to flow slowly in a more plastic fashion. For use in tremie or pumped concrete, the thickening agent must be used with a water-reducing admixture, generally a superplasticizer. Many

proprietary products contain the superplasticizer and the thickening agent in the admixture.

45. Tests at the US Army Engineer Waterways Experiment Station (WES) and Ben C. Gerwick, Inc., have indicated that combinations of antiwashout admixtures and superplasticizers in rich concrete mixtures can lead to entrainment of excessive air, between 9 and 14 percent. This excessive entrainment of air can be controlled by using a de-air-entrainment admixture such as tributyl phosphate or octy alcohol. The reasons for this entrainment and the conditions under which it occurs merit further study, as evidence exists that work performed in the North Sea may have encountered difficulties because of this problem.

46. Some proprietary anti-washout products are Rescon T, Hydrocrete, Betokem REP UV, Conplast 447, Pozzolith Hydrogel, Hydrocem, Joiluc, and Hydro-Beton. Experimental work at the WES and Ben C. Gerwick, Inc., has indicated that mixtures with water-cement ratios that range from 0.32 to 0.40 need only approximately one-tenth of the amount of antiwashout admixture recommended by the manufacturer. Test results indicate that higher addition rates of antiwashout admixture can be incorporated within the concrete by using melamine derivatives as the high-range water-reducer rather than naphthalene derivatives. Manufacturers consider typical concrete mixture proportions as having water-cement ratios that range from 0.45 to 0.65. At lower water-cement ratios, the antiwashout admixture binds up too much of the free water, leaving an insufficient quantity for fluidity.

47. A concrete designed specifically for underwater placement, hydrocrete, was used by the Kajima Corporation for underwater repair work in Japan. Where underwater abrasion was a concern, Kajima generally relied upon the incorporation of hard coarse and metallic fine aggregate to provide wear-resistance for concrete mixtures with water-cement ratios in the range of 0.5 to 0.6. The concrete was placed by pumping; it was allowed to drop exposed to water for only a few feet. This procedure minimized washout of the concrete paste and prevented a significant strength loss. Kajima frequently infiltrated the Hydrocrete through preplaced stone and rock, with the Hydrocrete serving as a binder. This procedure helped minimize cost and made use of the preplaced rock for abrasion resistance.

48. Pumping-aid admixtures, like antiwashout admixtures, prevent migration of water within the concrete mixture and provide a plastic behavior to

the mixture. However, as pumping-aid admixtures are not specifically designed to allow concrete to come in direct contact with moving water, some of these admixtures may not adequately inhibit the washing out of fines and cement.

Water-reducers and high-range water reducers

49. Conventional water-reducing admixtures and high-range water-reducers, or superplasticizers, are very important in achieving abrasion-resistant concrete for use underwater. Water-reducing admixtures also provide some set-retarding action; dosages 2 to 3 times those recommended by the manufacturer can retard the setting time from several hours to several days. Superplasticizers are more commonly used when large reductions in water content are required. Unfortunately, within 60 min, superplasticizers can exhibit rapid slump loss, which can severely impair underwater repair operations. High temperatures caused by the ambient temperature or by mixing, transporting, and placing can accelerate slump loss. Using superplasticizers and water reducers in combination can inhibit slump loss while achieving a good plasticizing action with a reasonable setting time.

50. In situations where long setting times can be tolerated, the use of very high dosages of conventional water reducers may be advisable, as they are less expensive than superplasticizers, and there should be no problem with slump loss. High dosages of water reducers would be useful for applications such as underwater vacuum processing where bleeding of the concrete and a delayed setting time, which would allow for revibration, are desirable. Also, the continuous mat used in this process would protect the surface of the fresh concrete from erosion.

Silica fume, pozzolans, and blast furnace slag

51. Pozzolans, including condensed microsilica fume, fly ash, natural pozzolan, and blast furnace slag, can reduce the heat of hydration of relatively rich underwater concretes. Pozzolans can also affect the workability, bleeding, cohesiveness, and strength of the concrete. The use of blast furnace slag is not significantly more beneficial than the use of portland-cement, except where large volumes of mass concrete are required. Even then portland-cement would probably be used to provide an abrasion-resistant cover for a blast furnace slag underfill. However, silica fume should be considered for use in underwater repair of stilling basins because it not only has a

pozzolanic effect on the concrete, but it also changes the physical hydration process within the concrete. The result is concrete with greater density, strength, and bond. It does not delay strength gain in the manner that other pozzolans do, and it can increase the cohesiveness of the fresh concrete against washout from moving water.

52. Because microsilica fume is a very fine material, the water demand required for good workability of the concrete mixture can be high; therefore, it must be used with a water reducer to prevent a loss in strength from an increase in the water-cement ratio. Addition rates of silica fume vary from 5 to 20 percent for underwater concrete; however, addition rates above 15 percent can significantly reduce the workability of the concrete and result in diminishing strength gains.

Polymer Concretes

53. Polymers are generally expensive compared to portland-cement concrete, but they prove economical for the repair of small areas or for thin layers unsuitable to conventional concrete. Polymer concretes considered in this report include:

- a. Polymer-impregnated concrete (PIC) (hardened concrete that is impregnated with a monomer which is subsequently polymerized within the hardened concrete).
- b. Polymer concrete (PC) (concrete, such as epoxy and resin concrete, that uses a polymer as a binding agent between aggregates).
- c. Polymer-portland-cement concrete (PPCC) (fresh portland-cement concrete, which is combined with a monomer, prepolymer, or a dispersed polymer to form a polymer network as the concrete cures).

54. In general, placing PIC underwater is not feasible. If it is used underwater, it has to be as precast panels that are lowered to the bottom of the stilling basin. However, studies have not shown PIC to be sufficiently abrasion resistant to warrant its use in precast panels. PC has demonstrated greater abrasion resistance than PPCC; however, PPCC may be appropriate for minor repairs.

55. The excellent abrasion resistance of certain types of PC might make its use in precast panels practical. However, the focus here will be on the use of PC that can be placed, cured, and used underwater. For a polymer

concrete to be applied to concrete underwater, it must not only cure but also bond underwater and match as closely as possible the mechanical properties of concrete. As the surface energy of most epoxies more closely matches that of water rather than that of concrete, most epoxies bead-up in the presence of water and, consequently, may not bond well with wet concrete.

56. At least one epoxy mortar appears to provide favorable properties underwater. The mortar with from 12.5- to 17.5-percent epoxy binder performed better when pumped up from the bottom, allowing the mortar to displace the water ahead of itself. Furthermore, it was suggested that the epoxy mortar be injected into small holes cut into the concrete at wide spacings so the mortar could displace the water ahead of it as it flowed over the concrete. The mortar seems to have excellent flow characteristics and should be able to flow 10 to 20 ft without a problem. In pull-out tests that measured the bond between the epoxy mortar and concrete, the test specimens failed in the concrete beneath the epoxy-concrete interface, indicating the bond between the epoxy mortar and the concrete exceeded the strength of the concrete itself.

57. Two proprietary, quick-setting epoxy resin concretes may be useful for small underwater concrete repairs. These products which have good bond and good strain compatibility with concrete, are useful for repairing cracks and small pockets; however, once mixed, they have a set time of only a few minutes. The 72-hr underwater abrasion test developed at the WES determined that one had an abrasion resistance of less than 0.05 percent by weight; the other less than 0.5 percent.

58. Prepackaged proprietary PPCC mortars have also been developed for use underwater. These products, typically, have good bond and a short setting time. They could probably be used by divers for local repairs as part of a preventative maintenance program. Two of these products identified by this study are Speed Crete by Tamms and Mari-crete by Atlas Minerals and Chemicals, Inc.

59. A patented method of underwater concrete repair using a PPCC mortar, an epoxy grout, and an epoxy putty has been developed by Reson RS of Sagetua, Norway. This method appears to be a very versatile and to provide good strength, good bond, and good strain compatibility with wet concrete underwater. Although designed for repair of vertical faces, this method has some aspects that could possibly be adapted for repair of horizontal faces.

Repairing underwater concrete with this method includes the following steps: (a) placing a form over the damaged area, (b) using an epoxy putty to seal the form, (c) injecting a special epoxy grout that bonds well with wet concrete into the form, and (d) filling the void and displacing the epoxy grout with a PPCC mortar.

60. Although latex-modified concretes and mortars exhibit good bond strengths to concrete and higher tensile and flexural strengths than conventional concretes and mortars, especially when used in thin layers, they are not recommended for underwater use. Latex-modified concretes and mortars need to dry to bring the dispersed latex out of solution to form a polymer network; therefore, while the concrete will cure underwater, there will be no benefit from the latex. Limited proprietary experimental evidence obtained at the University of California-Berkeley indicates that concretes with very low water contents, below 0.3 water-cement, may provide sufficient drying through self-hydration to form a polymer network within the concrete or mortar underwater; however, the increase in strength was not significant.

PART VI: COATINGS AND EPOXY COVERS

61. Polyurethane, some epoxies, and Densit provide very high abrasion resistance; however, these products are relatively expensive and may be difficult or impossible to place underwater in a fresh state in large quantities. Polyurethane cannot be applied to wet concrete; therefore, if used, it would have to be bonded to precast panels. Some epoxy coatings, particularly epoxy mortars, have some promise for use in thin layers underwater; however, the abrasion resistance of some of these products needs to be tested. Products such as Densit have excellent abrasion resistance but probably cannot be placed underwater by either pumping or tremie. One underwater epoxy coating developed in France has been used as a primer coat for epoxy mortars, a binder for epoxy mortars, for sticking elements on concrete, for injection, and for paint. It has demonstrated good adhesion underwater on various supports: concrete, stone, steel, and tile.

PART VII: METHODS OF PLACEMENT

62. The method chosen for underwater placement of concrete is determined by the type and quality of the concrete to be used for the repair. Different methods allow different degrees of workability of the concrete.

Tremie

63. Since most concrete technologists are well acquainted with conventional tremie techniques, these techniques will not be reviewed. However, if the tremie method is used with concrete that contains no antiwashout admixture, care must be taken to prevent washout from occurring when the tremie pipe is being filled or moved.

64. A good underwater concrete mixture for the tremie method relies upon the addition of fines--fine sand and 10 percent fly ash--to prevent harshness in the mixture. High dosages of superplasticizers and water-reducing admixtures allow for good flowability while delaying slump loss. The silica fume provides cohesion in the fresh concrete and strength and durability in the hardened concrete. The addition of admixtures will not correct a bad mixture proportion and should be used only to supplement a good mixture proportion. A sample of a good concrete mixture for use with the tremie method is

	kg/cu m
Cement with 10% fly ash	360
Silica fume	36
Coarse aggregate, 8-20 mm	858
Coarse sand, 0-12 mm	860
Fine sand, 0-8 mm	146
Water	146
Water-reducing admixture	7
Superplasticizer	7

w/c = 0.47, w/c + 5 = 0.42, slump = 23 cm, air = 2 percent

The Hydro-Valve Method and the KDT Method

65. The Hydro-Valve method, which was developed by the Dutch and is protected by a patent in the United States and many other countries, uses a flexible hose that collapses under hydrostatic pressure to place concrete. Concrete is put into the upper part of the hose, which is made by sealing the edges of two nylon sheets. When the weight of this concrete is great enough to overcome the combined hydraulic pressure and friction within the hose, a slug of concrete progresses down the hose and is placed underwater. The process repeats until enough concrete is placed. The outlet end of the hose is held at a constant level until the concrete spreads out, forming a slope of 1 on 5. This process is controlled by keeping the concrete level in the lower part of the valve between a minimum and a maximum mark. The transporting of the concrete in the water proceeds without turbulence or washing out. The level of concrete is built in successive layers (Figure 1). Concrete placed by this method can vary from very stiff to fluid. This method inhibits segregation of the concrete because of its slow movement down the hose. A tolerance of ±10 cm makes possible the installation of thin slabs. The concrete can be reinforced because the shield is kept at the upper level of the concrete. This device is simple and inexpensive. Any contractor who has personnel experienced in working in water can use it.

66. The Kajima's Double Tube (KDT) tremie method is very similar to the Hydro-Valve method. The KDT also uses a collapsible tube, but it is enclosed in a steel pipe that has many slits. This steel pipe makes possible withdrawing, moving horizontally, and re-setting the KDT. When the last slug of concrete goes down by its own weight, the water pressure from the water entering through the slits in the outer tube causes the tube to flatten. No water enters the tube, nor does washing of the concrete occur (Figure 2). The total amount of concrete placed by this method in 1976 was 32,000 cu m at 14 job sites. Field tests show this method to be reliable and inexpensive.

The A-Betong-Sabema and the Shimizu Pneumatic Valves

67. The A-Betong-Sabema pneumatic valve attaches to the end of a concrete pump line. This valve permits, restricts, or terminates the flow of

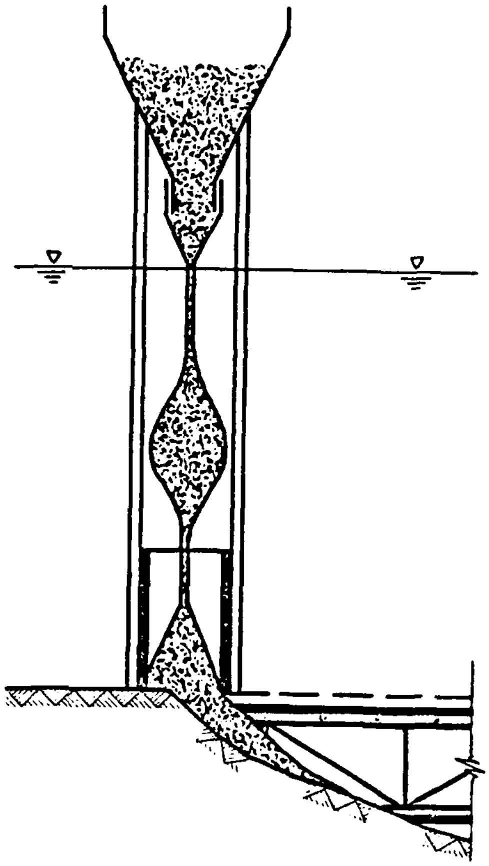

Figure 1. Hydro-Valve method

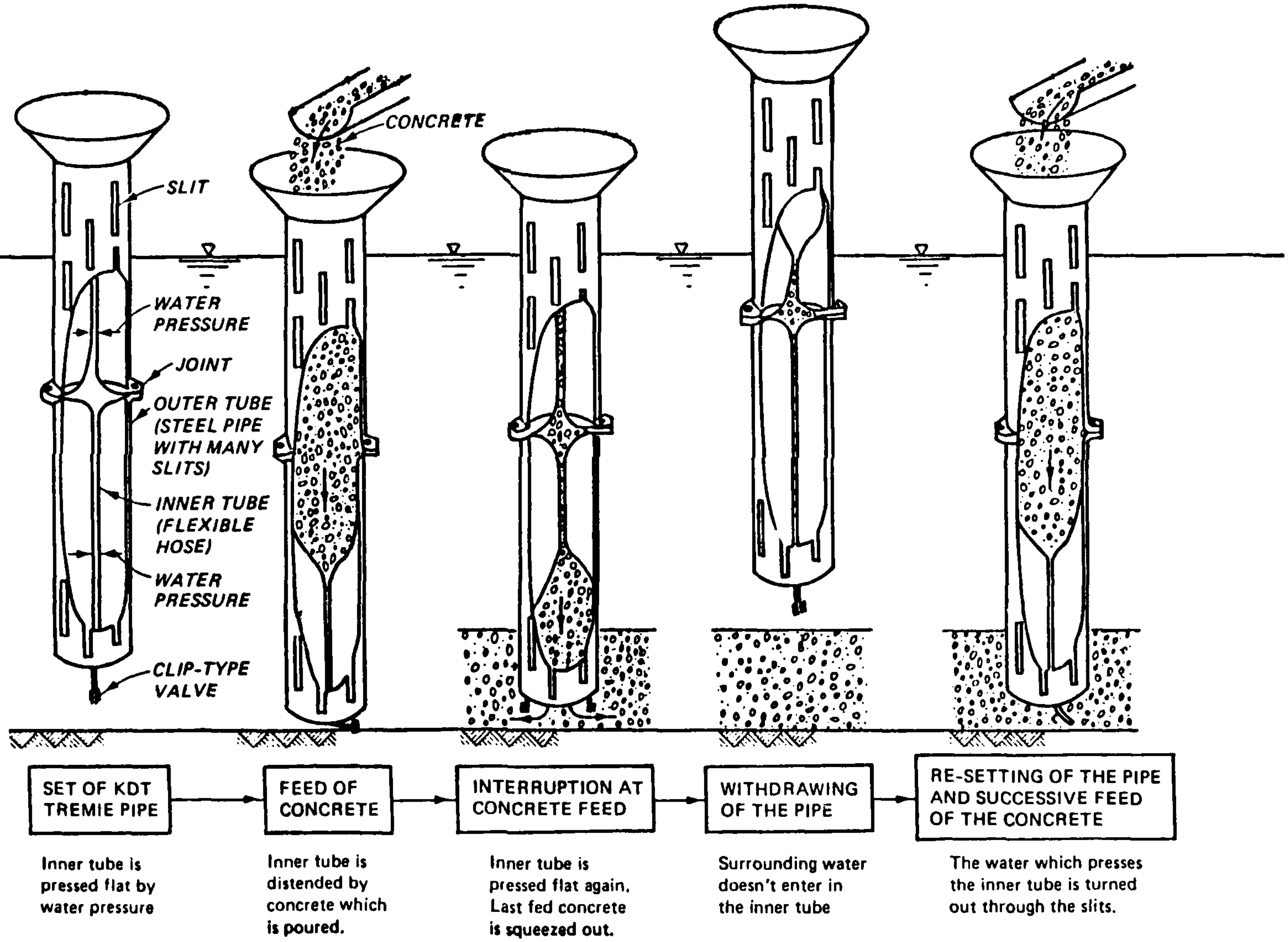

Figure 2. Kajima's Double Tube tremie method

concrete through the pumping line. The valve can control the rate of flow and the quantity of concrete placed during casting (Figure 3). When the boom is moved, the valve can be closed to protect the concrete line. The Swedish National Road Administration said that of a number of underwater concrete projects carried out from mid-1977 to mid-1979 only those executed by Sabema had no failures. The percentage of failure for other methods was never below 10 percent and was often much higher.

68. The Shimizu pneumatic valve, which is very similar to the A-Betong-Sabema pneumatic valve, incorporates a level detector with the valve unit. Placement of concrete continues until level detectors mounted on the tube sense that concrete has been placed to a predetermined depth. The valve is then closed, and the tube is repositioned.

69. Using pneumatic valves requires skilled workers who can avoid potential problems with plugging the line. This method is currently considered to be one of the best methods for underwater repair.

70. Another type of check valve that is placed at the end of the line is available. The valve which is designed for use in pumping concrete in underwater placing operations contains only one moving part. The valve is 18 in. long. One end fits a 5-in. pump line, and the other end, which is normally closed, is shaped like a duck's bill. The valve is constructed on a gum rubber reinforced with nylon fabric plies and is designed to open in up to 173 ft of water with a maximum line pressure of 100 psi. The valve does not require control from the surface, and the placing operation does not require the end of the hose to be immersed in the placed concrete.

Pumped Concrete

71. The underwater placement of concrete by pumping is very similar to the tremie method. However, in Europe and Japan pumping has superseded the tremie pipe for many applications for the following reasons:

- a. Concrete is transferred directly from the mixer to the point of discharge.
- b. Forcing the concrete under pressure eliminates some of the problems of gravity feed and vibration of the tremie pipe.
- c. Pumping with a boom permits better control during placement.

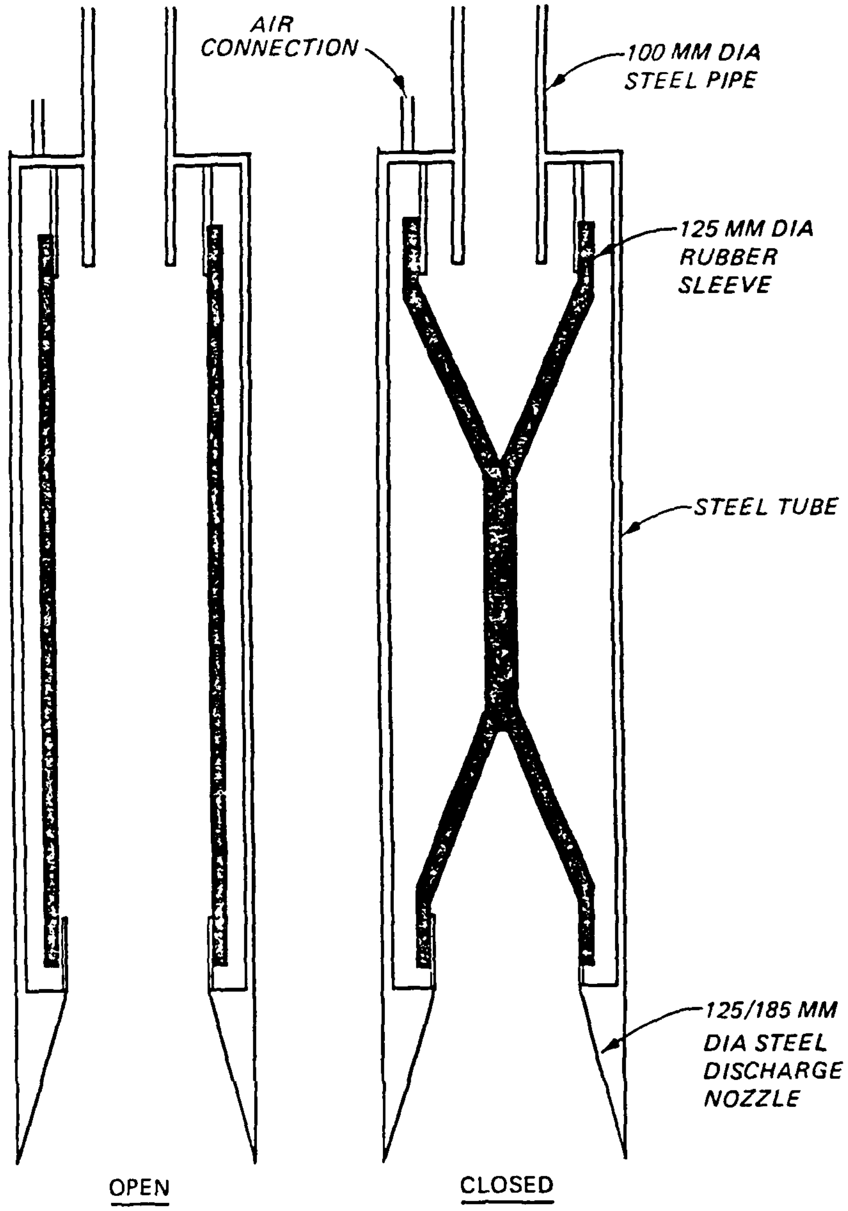

Figure 3. A-Betong-Sabema pneumatic valve

d. Because the concrete is under pressure, the discharge hose can be buried deeper within the placed concrete, thus reducing the constant need to lift and free the tremie pipe and risk segregation in the concrete.

72. The mixture should be checked for pumpability on land before underwater concreting begins. A plug at the end of the pump line will prevent segregation in the concrete when underwater placement begins. Care must be taken to prevent blockage of the pump line.

73. When pumping is used to place thin layers of concrete or to place concrete to tight tolerances, the use of a diver at the end of the pump line can be effective. By attaching a long handle to the end of the tremie pipe, the diver can make sure the end is buried in a thin layer of concrete and can guide the line as it is moved.

Preplaced-Aggregate Concrete

74. Preplaced-aggregate concrete is an effective method for repairing concrete underwater. The coarsely graded aggregate is enclosed in form work within the area to be repaired. Mortar or grout is then injected through the forms from the bottom of the preplaced aggregate. To disperse the water and to prevent the loss of fines and cement at the top of the repair, the top venting forms have a highly permeable fabric next to the concrete, backed with a steel grillage or wire mesh, supported by a stronger backing of perforated steel and plywood.

75. Because of the pressure generated by the grout beneath the forms, grouted doweling is usually required to hold down the forms. This pressure beneath the forms squeezes excess water out of the grout, thereby producing an abrasion-resistant surface similar to that obtained by vacuum processing. The use of the forms also guarantees a flat, even surface not possible with tremie or pumped operations.

76. Generally, an expansive grout with a fairly high water-cement ratio is used to provide fluidity. Even so, complete filling of voids is sometimes difficult when this method is used. However, interruptions to grouting operations are much less frequent than with either tremie or pumping operations, and additions of antiwashout admixtures to the grout makes possible the use of this method without the use of expensive forms.

Roller-Compacted and Plate-Compacted Concrete

77. Although roller-compacted concrete has never been used for underwater repair, its high abrasion resistance makes the development of this method an interesting possibility. At Tarbella Dam, roller compacted concrete survived two summers of operations with flows of 10-15 ft/sec plus waves, and the surface of the concrete was in excellent condition.

78. Traditionally, roller-compacted concrete uses zero-slump concrete. Because of the low water content and the high density produced by roller compaction, this concrete exhibits good abrasion resistance. With a jackup barge as a working platform, it might prove feasible to consolidate a stiff rich concrete underwater, using vibratory or pressure plate compaction or an actual roller with a mat or plate to protect the concrete. Antiwashout admixtures can be used in conjunction with this method.

The Bucket and Skip Methods

79. Underwater concrete can be placed by lowering a bucket or a bottom-dumping skip through the water and discharging the concrete onto either hardened or fresh concrete. An advantage of these methods is that they can place very stiff, dense concrete that can be consolidated with vibration or pressure compaction to produce a concrete with superior abrasion resistance. If a jackup barge is used with these methods, techniques can be developed which would allow for placement of such highly abrasion--resistant materials as Densit. An antiwashout admixture should probably be used with these methods to prevent segregation of the concrete.

Sibo Tilting Pallet Barge

80. The tilting pallet barge is used to place thin, uniform layers of concrete in shallow water. The concrete is spread in a uniform layer on the deck of the barge and is then dropped beneath the water by tilting pallets. This method, which requires the use of antiwashout admixtures, can be used in deeper water by lowering a skip with tilting pallets to the bottom. This barge was constructed by Sibo of Osnabruck, Germany.

Inclined Tremie

81. The US Army Engineer Waterways Experiment Station (WES) is examining the possible use of an inclined tremie for placement of thin layers of concrete. The concrete will slide down a vibrating, inclined chute to the bottom. This method will require the use of antiwashout admixtures.

Prefabricated Panels

82. The Naval Civil Engineering Laboratory is examining the possible use of prefabricated panels for underwater placement; however, this method of placement has problems that must be overcome. Grouting beneath the panel creates uplift pressures which must be resisted by doweling the panels to the underlying concrete or by adding temporary weights to the panels. Also, discontinuities at the joints and voids beneath the panels from bleeding or incomplete filling are conditions which allow high-velocity water to tear the panels from the underlying concrete.

PART VIII: ADDITIONAL CASE STUDIES

83. The following cases were investigated during this study in addition to the international examples of underwater repair technology cited.

Tarbella Dam--Pakistan

84. Horace Johnson, formerly of the US Corps of Engineers and TAMS's resident engineer at Tarbella Dam during repair work, provided the following information. Broken chunks of concrete from the spillway and sections of steel tunnel lining scoured very large holes through the slab of the stilling basin down to bedrock. Repairs consisted of filling the holes with tremie concrete, dewatering, installing drilled and grouted anchors, and then placing a 24-in.-thick steel fiber reinforced concrete slab. Over 30,000 cu m of concrete were required to fill the scoured area. Repairs have apparently proved fully satisfactory.

The Swedish State Power Board

85. The Swedish State Power Board operates almost 200 dams, most of them small, low-head dams. However, 6 dams are over 50 m high and have concrete spillways and stilling basins, Only 2 of these structures have suffered serious erosion in the spillway and stilling basin.

86. Repairs have been carried out in the dry by dewatering, cutting out the damaged concrete, and repairing the top mat of reinforcing steel. Then concrete with a very low water-cement ratio is placed over surface-dry concrete. Board members felt this method improved the bond without increasing the water-cement ratio at the interface. Superplasticizers, but not silica fume, were used in the concrete mixture. Neither anchors, epoxy bonding compounds, nor surface coating was used; however, repairs to date are satisfactory.

Spie-Batignolles Batiment Travaux Publics-France

87. Mr. Paul Poitevin of the Spie-Batignolles Batiment Travaux Publics, France, reported that most of their repair work for concrete structures

subjected to abrasion have been conducted in the dry, using epoxy resins with and without steel fibers. Mr. Poitevin further suggested that rubber may be useful in repairing structures subjected to abrasion.

England and the North Sea

88. Considerable research regarding the repair of concrete structures in the North Sea has been conducted in England. This information, though not directly related to repairing abrasion-damaged structures, provides important background information. Three technical publications concerning underwater repair of concrete include:

Hill, T. B. 1984 (May). "Underwater Repair and Protection of Offshore Structures," Concrete, pp 16-17.

Billington, Colin J. 1979 (April). "The Underwater Repair of Concrete Offshore Structures," OTC 3464, Wimpey Laboratories: Proceedings of Offshore Technology Conference, pp 927-937.

Humphrys, B. G. 1979. "Underwater Repair of Concrete," Preprint No. 8168, Society of Petroleum Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers.

The Sibo Group--West Germany

89. To date most of the work the Sibo Group of West Germany has performed on underwater concrete has been for riverbank and canal stabilization. This work indicates that antiwashout admixtures such as those used in Hydrocrete work well for grouting through preplaced aggregate.

PART IX: EXPERIMENTAL RESEARCH CONDUCTED AT THE UNIVERSITY OF CALIFORNIA-BERKELEY

90. A limited experimental study to examine high-strength concrete mixtures containing different combinations of silica fume, antiwashout admixtures, superplasticizers, water reducers, and steel fibers has been initiated at the University of California-Berkeley. Test results are as follows:

- a. Manufacturers' recommended dosages of antiwashout admixtures are generally too high for rich mixtures with low water-cement ratios: the concrete has a zero slump and is not workable.
- b. One tenth the manufacturer's recommended dosage of antiwashout admixture seems to be appropriate for rich mixtures with low water-cement ratios.
- c. Addition rates of antiwashout admixtures seem to be highly sensitive to water contents within the mixture.
- d. The combination of antiwashout admixtures and superplasticizers can result in the entrainment of excessive air within the mixture.

Mixture 1 (Control Mixture):	lb/cu yd
Cement (C)	750
Microsilica fume (MSF)	113
Water (w/c+msf=0.32)	276
Fine Aggregate (Oly. "O")	1,072
Coarse Aggregate (MSA=3/8")	1,800
WRDA-19 (superplasticizer)	204 (oz/cu yd)
Plastiment (water reducer)	50 (oz/cu yd)
Unit Weight (measured)	150.7 lb/cu ft
Air Content (measured)	2 percent
7-day Compressive Strength	8,000 psi
Slump (measured)	6 in.

Mixture 2:

(Same as 1 above except the following)

Rescon T	2 lb
WRDA-19	250 (oz/cu yd)
Plastiment	4 oz/100 lb (c+msf)
Unit Weight (measured)	130 lb/cu ft

Air Content (measured)	14 percent
7-day Compressive Strength (low due to presence of air)	4,350 psi
Slump	5.5 in.

Mixture 3:

(Same as 2 above except the following)

Steel Fibers (Harex)	200
Coarse Aggregate	1,756
Unit Weight (measured)	130 lb/cu ft
Air Content (measured)	17.5 percent
7-day Compressive Strength	5,030 psi
Slump	5.5 in.

PART X: RECOMMENDATIONS

91. The following recommendations are preliminary and subject to change as work progresses.

Preferred Methods

92. Techniques for the underwater repair of concrete structures can be broadly categorized as simple or sophisticated. The simpler method involves the use of pumped concrete, the tremie pipe, the Hydro-Valve, the KDT, the inclined tremie, or a bottom-dumping or tilting-pallet skip. The concrete for such operations should have a silica fume content greater than 10 percent and a water-cement ratio less than 0.36. It should contain an antiwashout admixture and probably a superplasticizer and a set-retarding water reducer.

93. The more sophisticated method, which would require further development of techniques and equipment, would make use of a stiffer, denser, stronger concrete that would require some underwater compaction and finishing. This method would require a support vessel to aid in surface preparation, placement, compaction, and finishing. The concrete should have a water-cement ratio of less than 0.34, a silica fume content between 10 and 20 percent, a set-retarding water reducer, a superplasticizer, and probably an antiwashout admixture. Polymer mortars should be considered for small underwater and thin-layer repairs.

Future Research

94. The following areas merit further investigation:

- a. The refinement of a high-strength, self-consolidating plastic mixture for use as a pumped concrete.
- b. Development of fiber-reinforced concrete mixture which does not accelerate abrasion.
- c. Development of methods for underwater compaction, including a vibrating screed and a vibrating pressure plate.
- d. The effect of vacuum processing with an overpressure of from one to three atmospheres.

e. Field testing to correlate the abrasion resistance of in situ concrete with concrete subjected to the 72-hr underwater abrasion tests developed at WES.

f. Testing polymer mortars for underwater abrasion resistance.

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